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LCA FOR ENERGY SYSTEMS

Heating systems LCA: comparison of biomass-based appliances

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Abstract
Purpose Biomass provides an attractive solution for residential heating systems based on renewable fuels, even though biomass-based domestic heating systems are recognized as significant particulate matter emitters; thus, a life cycle assessment (LCA) approach was used in the study to compare two different appliances: a wood stove and a pellet stove, both modeled according to the best available technologies definition.
Methods System boundaries of each scenario refer to a cradle-to-grave approach, including production, use and disposal of the heating appliance, as well as the preparation of biomass feedstock. The assessment of environmental impacts was performed assuming 1 MJ of thermal energy as the reference flow, considering the categories of particulate matter formation, human toxicity, climate change, and fossil fuel depletion, according to the ReCiPe 1.07 method. Finally, the comparison was extended to certain innovative heating systems in order to qualitatively evaluate potential improvements in residential heating performances.
Results and discussion The results show that the wood stove reaches the highest scores in the categories of particulate matter formation and negative effects for human toxicity, as a consequence of the stove's lower combustion efficiency, which would lead to a preference for the pellet stove. However, when climate change affecting human health and the ecosystem, and fossil depletion are considered, the choice appears more uncertain due to the energy consumption from the pelletizing step. Alternative technologies (e.g., solar panels in combination with a gas boiler) show better scores related to fine particles emission reduction, even if a worsening in other categories is observed. The results were validated by a sensitivity analysis.
Conclusions The study suggests that a LCA approach can support the choice of the best domestic heating system, helping to promote policy initiatives on a sound basis and to understand which are the main key levers to act for reducing the total environmental burdens of biomass-based heating appliances.

Keywords Domestic heating · Heat generation · Particulate matter formation · Pelletizing · Residential stoves · Wood biomass

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1 Introduction and aims of the study

Since ancient times, biomass has been a versatile and renewable energy source for humanity. Thanks to its easy supply and relatively high heating value, biomass was used for a long time in many applications, from cooking to spatial heating, lighting, and steam production. The subsequent replacement of biomass with fossil fuels led humans to rely on a higher performance primary energy form for anthropogenic activities, but one which was exhaustible, polluting, and not uniformly distributed around the planet.

With the rising concerns in the more developed countries over energy dependence on fossil fuels and the environmental hazards connected with global warming, energy policies started to trend toward renewable energy sources (Verma et al. 2009). In Europe, the Directive 2009/28/EC promotes the use of woody biomass as feed in combustion plants to produce heat or electricity and to reduce nonrenewable resource consumption. Scaling down from industrial combustion

plants to residential systems, biomass feedstock provides an attractive option for domestic heating needs, where fossil fuels account for about 15 % of the total energy consumed in that sector throughout Europe (Verma et al. 2009). Biomass resources are more available locally, and they are commonly recognized as having better environmental implications thanks to a lower contribution to global warming, supporting the goal of achieving a Low Carbon Society (Madlener and Koller 2007). However, the carbon balance should be carefully evaluated and different performances on the environment (e.g., land use occupation and depletion) may result whether or not energy-related implications from dedicated crop cultures are considered. Besides, there is some concern over their usage in residential heating due to the emissions of various pollutants, such as polycyclic aromatic hydrocarbons, NO_x, CO, SO_x, and particulate matter (Solli et al. 2009; APAT-ARPA Lombardia 2008). Both the gas emission regulations contained in EU legislation for protecting the population and the environment and technological progress have led to more efficient combustion processes and emission control, thus helping to counter the negative effects connected with residential heating systems. In any case, an intensive use of biomass stoves in highly populated urban areas, obsolete appliances, bad common practices in stove combustion and maintenance, and geographical micro-area conditions may cause a worsening of air quality and related health issues (Verma et al. 2009; APAT-ARPA Lombardia 2008).

In Italy, microclimate conditions and an intense industrial activity have combined to create critical air quality conditions in urban areas of the Po Valley. In 2006, a survey conducted in Italy revealed a significant contribution to PM_{10} from the use of biomass for residential heating (ISPRA 2012); 2 years later, another study was started for the purpose of estimating in detail the amount of particulate matter formation from biomass heating appliances (APAT-ARPA Lombardia 2008). The study quantified an amount of about 84,000 tons, which is equal to 30 % of total PM_{10} emissions from all anthropic sources in the same year. On the other hand, benefits from CO_2 emission savings were estimated at 9 Mt or 2 % of carbon dioxide emissions in the year 2005 (APAT-ARPA Lombardia 2008). To prevent pollution and preserve air quality, some Italian regions have banned biomass-based heating systems not complying with certain technical specifications (e.g., Lombardy Regional Law no. 24, 2006). Although environmental monitoring is widely performed by environmental agencies in urban areas to study the burdens and repercussions of combustion processes on human health and the ecosystem, only a few studies in literature have used a life cycle approach when focusing on wood biomass heating systems (Solli et al. 2009; Roedl 2010; Caserini et al. 2010; Bonoli 2007; Bidini et al. 2006). Indeed, such an approach would provide a concrete contribution to the search for the best option, by comparing all the material and energy flows involved in the different residential heating systems.

In the present study, life cycle assessment (LCA) methodology is applied to create a model for comparing the environmental impacts of two wood-based combustion systems: a wood and a pellet stove included among the best available technologies (BATs) according to the definition given in the European Commission DG TREN report (2009a). The model was used to obtain a screening analysis of the two solutions, based on literature studies and local information relevant to the region of Lombardy; this could provide a reliable basis which can be improved with further data from direct monitoring campaigns. Unlike other studies, no dedicated crops were assumed for fuel production, but only spontaneous biomass. The comparison between wood and pellet stoves was carried out in terms of thermal energy produced. Such a functional unit was chosen in order to make the model suitable for extending system boundaries to other heating systems such as domestic boiler or advanced integrated systems (e.g., heating pump or solar panels). An uncertainty analysis was performed to check the robustness of the model. The environmental impacts resulting from the two systems investigated were assessed using the ReCiPe method for the following midpoint categories: climate change affecting the human health (CH) and the ecosystems (CE), human toxicity (HT), particulate matter formation (PMF), and fossil depletion (FD).

2 Methodology

2.1 System boundaries and functional unit

A cradle-to-grave approach was adopted in order to provide an overview of the whole heating systems being studied. System boundaries include the stove manufacture, usage phase (i.e., heat generation), and final disposal. All the inward and outward flows within the system boundaries were considered in the study, such as energy sources, material types, and waste. In Italy, forest areas are expanding and covered around 9–10 million ha of national land in 2010, whereof up to 81 % available for wood supply (FAO 2011; INFC 2007): as a consequence, most of the consumers collect timber locally (Pastorello and Dilara 2010). Thus, in the study, it has been estimated that no dedicated biomass cultivation was necessary for the biomass supply, i.e., biomass was assumed to derive only from forest branches and woody discards, while dedicated cultivations such as Short Rotation Forestry were not modeled for the intended goal. Therefore, in a first approximation, environmental impacts from the biomass logs supply were allocated to the cutting phase only, and consequently, the burdens resulting from agricultural land occupation and from the cultivation phase

(e.g., the use of herbicides, Roedl 2010) were not included in the study. Although this assumption may be arguable, the choice is also justified by the Directive UNI EN 14961-5/2011 *Solid biofuels—Fuel specifications and classes—Part 5*: *Firewood for non- industrial use*, which underlines the possibility to use wood residues and chemical untreated wood residues as fuel for stoves.

The two systems modeled were compared on the basis of 1 MJ of thermal energy produced as the functional unit. This choice is supposed to lead more directly to the assessment of the environmental performance connected with domestic heating appliances. Furthermore, it appears more suitable for subsequently extending the comparison to other domestic heating systems.

2.2 Description of heating systems and biomass supply

The two heating systems were modeled in accordance with the BAT definition for wood and pellet stoves (DG TREN 2009b): the scenarios were named respectively "wood stove" and "pellet stove" and modeled as described below. Next paragraphs list in detail the main inventory for data and differences between scenarios: in particular, composition and operating characteristics for the stoves and properties for wood and pellet feedstock are explained.

2.2.1 Wood stove scenario

This scenario considers a wood stove with a nominal power of 15 kW and an average combustion efficiency of 60 %. A common lifetime of 35 years was also assumed (DG TREN 2009a, b). Inventory includes data collection for the infrastructure, transportation, combustion process, and end-use treatments of the stove. The main materials input in the production process, used in the manufacturing of the furnace and chimney, comprises steel (104 kg), drawing and rolling steel (1.75 kg), concrete (0.059 m^3), rock wool (1.75 kg), and lubricating oil (0.1 kg). Air emission processes from the combustion phase referred to the Ecoinvent 2.2 database. An ash amount of 3 % was estimated (Probio CTI 2004), and, according to the Italian law (Legislative Decree no. 152 of 3/4/2006) that forbids the use of ash for agricultural purpose, the final disposal was assumed to be half to incineration treatment and half to landfilling. At the end-of-life stage, the wood stove was assumed to undergo dismantling processes for steel removal for eventual recycling, while the remaining materials would be landfilled. The savings from the steel recycling process were assumed to be 84 and 87 % for primary metals and energy, respectively, in accordance with reports in literature (Istituto di Ricerche Ambiente Italia 2006; Stiller 1999).

In terms of biomass feedstock, this scenario was modeled assuming the combustion of wood logs needed to produce 1 MJ of thermal energy. Data inventory for the moisture content, density, and lower heating value (LHV) were assumed consistently with the Ecoinvent 2.2 Database and UNI EN 14961:2011. The biomass fuel classes chosen to model this scenario belong to the A1 and A2 categories (UNI EN 14961-5:2011), which include not only firewood produced by stem wood and whole trees without roots but also wood residues (chemical untreated wood residues and log residues). Both classes of timber have similar moisture levels and size (in terms of diameter and length) and represent firewood suitable for use in stoves and fireplaces. For the analysis, the wood burned was assumed to belong to deciduous species, representing those most used in northern Italian regions and around 93 % in Lombardy (ISTAT 2008). An average composition of 50–50 % hardwood and softwood was chosen; this assumption is in line with other estimates (INFC 2007), confirming poplar (softwood) and beech (hardwood) as the two most important deciduous species in the country. This estimation implies a density value of 660 kg/m^3, an average LHV of 13 MJ/kg, and moisture level of around 20 % (AIEL 2012).

Following a cradle-to-grave LCA approach, material and energy flows referring to fuel production were included in the study: a chain of feedstock was supposed in which woods are felled by chainsaw and transported by tractor over a distance of 10 km. After a drying period to reduce moisture, timber discards are distributed to final consumers by truck; an average distance of 240 km was assumed, mediated from a range of values used in previous works (the highest found in Caserini et al. 2010, and lowest in Bonoli 2007). The main information on the inventory phase for the wood stove scenario is reported in Tables 1 and 2.

2.2.2 Pellet stove scenario

This scenario models a pellet stove with a nominal power of 15 kW, an average combustion efficiency of 64 %, and an average lifetime of around 12–13 years (European Commission 2009b). The infrastructure process includes the following material flows used for appliance manufacture: steel (500 kg), drawing and rolling steel (5 kg), concrete (6 m^3), rock wool (5 kg), aluminum (0.17 kg), cast iron (12 kg), polyethylene (1.2 kg), and lubricating oil (0.4 kg). It also includes the surface for furnace and wood chip storage, transport, and energy used for the construction and disposal of the furnace. The same Ecoinvent process for steel iron recycling used for the wood stove was here included, assuming 84 % recycling efficiency and 87 % energy savings (Istituto di Ricerche Ambiente Italia 2006; Stiller 1999). Disposal processes for concrete, oil, polyethylene, copper, and aluminum were also modeled.

In accordance with previous studies, it was hypothesized that the raw material for pellet production came exclusively from wood discards—sawdust or wood chips—since around

Table 1 Inventory phase: main aspects for each scenario modeled

Parameters	Wood stove	Pellet stove
Estimated net fuel use efficiency[a] (%)	60	64
Power (kW)	15	15
Average lifetime (years)	35	12.5
Fuel chain	Wood from forest and discards	Raw materials from wood discards
Wood composition	50 % hardwood	28 % hardwood
	50 % softwood	72 % softwood
Life cycle approach	Cradle-to-grave	Cradle-to-grave
Fuel moisture (%)	20	10
Fuel LHV (MJ/kg)	13	17
Fuel density (kg/m^3)	660	715
Main air pollutants modeled	$PM_{2.5}$, CO_2, CO, NO_x, PAH, dioxins, heavy metals	$PM_{2.5}$, CO_2, CO, NO_x, PAH, dioxins, heavy metals
Ash amount *w/w*	3 %	2 %

[a] Estimated net fuel use efficiency is estimate for the net efficiency of each scenario throughout all seasons including part load operation, transient operation, degradation of performance over time, etc. (European Commission, DG TREN 2009a)

Table 2 Main input and output processes for the biomass heating scenarios investigated

Process	Unit	Biomass heating scenarios	
		Wood stove	Pellet stove
Input			
Feedstock			
Hardwood	m^3	9.50E−05	3.64E−05
Softwood	m^3	9.50E−05	9.36E−05
Energy			
Electricity	kWh	–	2.43E+02
Diesel	kg	1.78E−01	–
Output			
Main air pollutants			
$PM_{2.5}$	kg	1.46E−04	3.33E−05
CO_2	kg	1.17E−01	1.24E−01
CO	kg	2.88E−03	1.23E−04
NO_x	kg	2.00E−04	8.97E−05
PAH	kg	1.39E−08	1.42E−08
Dioxins	kg	3.88E−14	3.97E−14
Arsenic	kg	1.25E−09	1.28E−09
Cadmium	kg	8.75E−10	8.97E−10
Chromium	kg	4.95E−09	5.07E−09
Copper	kg	2.75E−08	2.82E−08
Lead	kg	3.13E−08	3.20E−08
Mercury	kg	3.75E−10	3.84E−10
Nickel	kg	7.50E−09	7.69E−09
Zinc	kg	3.75E−07	3.84E−07
Ashes			
Incineration	kg	1.92E−03	9.19E−04
Landfill	kg	1.92E−03	9.19E−04

90 % of all Italian pellets are produced in such a way (Vivarelli and Ghezzi 2009). Thus for the modeling, a pellet of class B (UNI 14961-2:2011) was assumed: a category that includes fuel produced from by-products and residues from the wood processing industry, with a moisture level of 10 %, ash amount of 2 %, and density and LHV values of 715 kg/m^3 and 17 MJ/kg, respectively (Ecoinvent Centre 2009, UNI 14961-2:2011). An average composition of 72 % softwood and 28 % hardwood was considered in order to obtain the correct amount of lignin used as the natural binder in the pelletizing process. Also, the pellet stove scenario includes the steps required for pellet production: the grinding, drying, conditioning, and extrusion processes, with their energy consumed per kilogram of product. An average value of 0.338 kWh/kg was assumed (Bidini et al. 2006; EMPA 2001; Gustavsson and Karlsson 2001; Caserini et al. 2010; Gmur 2000; UMBERRA 2000; Ecoinvent Centre). Even in this case, considering the capacity of the pellet producers in Lombardy, it was assumed that regional pellet production is able to meet the demand within that territory. For the distribution of the pellets, an average distance of 30 km, covered by truck, was assumed. Similar to previous scenario, ash final disposal was modeled half to incineration and half to landfilling. The main aspects for the pellet stove scenario are listed in Tables 1 and 2.

2.2.3 Alternative domestic heating scenarios

An investigation of the most widespread alternative technologies for domestic heating currently available on the Italian market was carried out to permit a comparison with biomass appliances in terms of environmental midpoint categories. For this purpose, the modeling phase was carried out using

Ecoinvent 2.2 database processes (Ecoinvent Centre 2009) and collecting other data from literature. Three heating appliances were identified as the most suitable for the comparison: gas boiler, solar heating panel, and heat pump. A short description of the main characteristics is provided below.

A condensing gas boiler with a power of 10 kW and average lifetime of 17 years was considered (Kemma et al. 2005). This scenario includes the fuel input from a low-pressure network, infrastructure, emissions, and electricity needed for its operation. Natural gas was chosen for the boiler instead of liquefied petroleum gas, as it is the most widely used gas for heating appliances in Italian homes.

A heating solution using a solar panel with a glazed flat plate collector was included as the renewable energy-based technology with the best performance in terms of lowest heat dissipation; 15 years were assumed as the average lifetime (Ardente et al. 2005; ENEA 2009; Pauschinger et al. 2003). To achieve the desired heat performance in an ordinary home, a combined system with gas boiler might be necessary, particularly during the winter season. Processes include infrastructure, maintenance operations, and electricity used for fluid movement (e.g., pump use).

Lastly, a heat pump electric air–water technology was modeled: in spite of the fact that such a scenario is still rather uncommon for heating purposes, it could play an important role in the near future. A power of 10 kW and average lifetime of 20 years were assumed (Acerbi 2009). Processes include infrastructure, electricity produced by energy mix, and refrigerant emission.

2.3 Data quality and sensitivity analysis

Scenarios were modeled using literature data sources and the Ecoinvent 2.2 database processes (Ecoinvent Centre 2009) for energy and fuel production, infrastructure, transport, disposal, and air emission processes. Among the goals of the study is the creation of a reliable model to be implemented using primary data collected from a direct environmental monitoring campaign on stove emissions.

The “Data pedigree matrix” by Weidema and Wesnaes (1996) was applied to estimate uncertainty ranges of data in order to check the reliability of LCIA results. The matrix attributes data quality scores ranging from 1 (best) to 5 (worst), according to the following sources of uncertainties that may affect a method’s reproducibility and robustness: data representativeness, acquisition methods, and temporal, technological, and geographical data correlations. The values obtained were used to develop a Monte Carlo analysis, performed to evaluate the model’s sensitivity.

Also, the main sources of uncertainty for biomass scenarios were studied to assess repercussions on the total results. For the wood stove scenario, a previous study (Caserini et al. 2010) reported that only 50 % of the timber used in domestic heating appliances comes from Lombardy, while the rest is imported from other Italian or European regions. In our model, this estimation assumed 450 km as the maximum distance from import trade partners, while a minimum of 30 km was used as the shorter distance for the domestic production (Bonoli 2007). On the other hand, the main variability for the pellet stove scenario is associated with the energy consumption during the pelletizing processes: depending on the process conditions, such as natural or artificial drying, conditioning, and extrusion technology, the energy demand is estimated at from 0.0629 to 0.681 kWh/kg (Bidini et al. 2006; EMPA 2001; Gustavvsson and Karlsson 2001; Caserini et al. 2010; Gmur 2000; UMBERRA 2000; Ecoinvent Centre 2009).

3 Results and discussions

3.1 Biomass scenarios

Impact analysis was carried out using SimaPro 7.3.3 software (Pré Consultant 2010), and the ReCiPe 2008 v 1.07 method (Goedkoop et al. 2012) was followed for the assessment of environmental burdens for the midpoint categories CH, HT, PMF, CE, and FD, which can be later grouped into three endpoints for damages to human health, ecosystem quality, and resource consumption (Goedkoop et al. 2012). Units of measurement are as follows: disability adjusted life years for human health, potential disappeared fraction of species (species × year) for ecosystem quality, and increased cost ($) for resource consumption. The results of the characterization analysis at the midpoint level are briefly reported in Table 3.

Overall, the scores show that the wood stove produces the highest impact for HT and PMF compared to the pellet stove, while the latter presents the worst results in the CH, CE, and FD categories. Figure 1 shows the results in terms of midpoint (percentage): the radar chart gives a quick overall view of the environmental loads from each scenario. A discussion for each impact category is presented in the following

Table 3 Impact assessment results for each category considered

Impact categories	Unit	Wood stove	Pellet stove
Climate change human health	DALYs	2.37E−08	4.54E−08
Human toxicity	DALYs	5.33E−08	2.81E−08
Particulate matter formation	DALYs	7.55E−08	2.82E−08
Climate change ecosystems	species × year	1.34E−10	2.57E−10
Fossil depletion	$	7.68E−04	1. 49E−03

DALYs disability adjusted life years, *species × year* species disappeared per year, *$* increasing resource cost

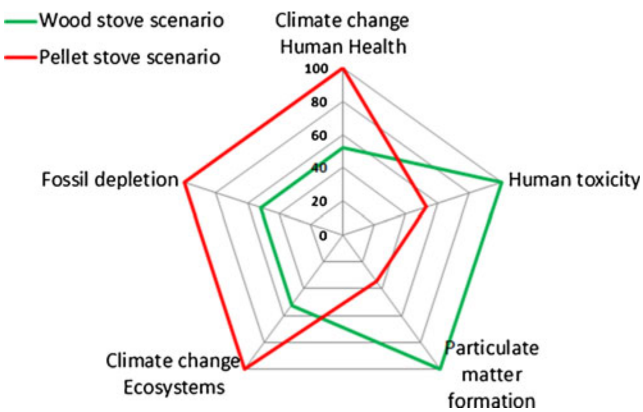

Fig. 1 Radar chart showing results in terms of single point (by percentage). Impact categories are at *vertexes of the radar*, while the *lines* lay in correspondence of the share gained by each scenario

sections. Table 4 summarizes the main processes or substances for each environmental midpoint category studied, as resulting from the contribution analysis.

Table 4 shows that for both scenarios the ash final disposal processes entail the highest contribution to human toxicity: 40 to 48 % from incineration and 39 to 46 % from landfill disposal when considering pellet and wood stove, respectively. Impacts from the incineration process include air and water emissions, auxiliary material consumption for flue gas cleaning, and the disposal of residual material such as solidified fly ash and scrubber sludge in landfill. On the other hand, landfilling is a common practice in Italy, and harmful effects may be caused by the release of heavy metals such as cadmium, zinc, manganese, and lead into groundwater basins, thus leading to potential exposure risks for humans (CTI Energia e Ambiente et al. 2004). The contribution analysis also revealed that the damage to human health resulting from direct emissions during the combustion phase is less than 10 % (3 and 5 % for the wood and the pellet stove, respectively).

The PMF midpoint has the highest contribution from the combustion phase, which seems to cause up to 60 and 88 % of substance emissions reported in Table 4 for the pellet and the wood stove, respectively; the remaining fraction is due to the transportation and auxiliary fuels contribution. The PMF takes into account both the direct particulate emitted by the plant and precursor substances such as NO_x and SO_2 emissions. As known, the particulate toxicity is influenced by dimension and chemical composition of the particle. For this reason, we decided to verify for each scenario which substances contribute mainly to the category. The contribution analysis results in Table 4 show that for the wood stove scenario the highest impacts are primarily due to the emission of fine primary particulate $PM_{2.5}$ (69 %), and then to the secondary particulate produced by NO_x and SO_2 (29 %). PM >2.5 μm counts for about 1 %. The pellet stove scenario, on the other hand, shows that the finest particulate contributes for 43 %, while a higher contribution from the secondary particulate comes from NO_x (38 %) and SO_2 (16 %) emissions. The results are in line with the outcomes reported in literature studies (Caserini et al. 2010; AIEL 2011; Bäfuer et al. 2011). Generally speaking, variables that affect PM composition, size, and effects on human health depend on the stove's combustion and pollutant removal efficiency on one hand, and the fuel type and composition on the other. The pellet stove has the advantage of higher efficiencies, and the fuel has greater energy density, size, and moisture content, more suitable for better combustion performance. In any case, the higher quantity of secondary particulate is associated with pellet combustion, due to the

Table 4 Process contributions to impact categories by percentage

Impact categories	Wood stove	Pellet stove
Human toxicity	48 % ash disposal	40 % ash disposal
	46 % ash in land farming	39 % ash in land farming
	3 % combustion process	5 % combustion process
	3 % other	16 % other
Particulate matter formation	69 % $PM_{2.5}$	43 % $PM_{2.5}$
	28 % NO_x	38 % NO_x
	1 % SO_2	16 % SO_2
	1 % PM_{10}	2 % PM_{10}
	1 % other	1 % other
Climate change[a]	71 % CO_2	89 % CO_2
	21 % N_2O	5 % N_2O
	7 % CH_4	5 % CH_4
	1 % other	1 % other
Fossil depletion	82 % oil production	29 % oil production
	5 % coal production	18 % coal production
	4 % natural gas production	49 % natural gas production
	9 % other	4 % other

[a] The Climate Change category includes processes contribution to both the human health and the ecosystem damage categories

nucleation, agglomeration, and condensation processes involving the NO_x and SO_x species.

Climate change (CC) and FD categories are closely related, due to the CO_2 equivalent emission factor resulting from combustion processes. The CC midpoint entails effects at a more global scale than the other impact categories. Both scenarios show similar percentage contributions to the climate change midpoint, due to direct greenhouse gas emissions, where carbon dioxide plays the largest role, followed by nitrous oxide. In any case, although wood pellet size distribution leads to an efficient combustion (Fiedler 2004; Heschel et al. 1999), the pellet stove almost doubles the CC environmental impact compared to the wood stove (Figs. 1 and 4); the reasons must be sought in the pelletizing phase. This process comprises several operations in which large quantities of energy are required, such as the drying, conditioning, and extrusion steps. Consequently, the fossil fuel consumption, mainly in terms of natural gas, depends on the chemical and physical characteristics of the pellet produced; for example, moisture content of less than 10 % may indicate a reduction of the drying phase and a decrease in CO_2 emission. However, as pointed out above, the pelletizing phase is affected by a wide range of uncertainty, mainly related to the technological systems used by plants.

The percentage contribution to fossil depletion listed in Table 4 for the wood stove scenario shows, on the other hand, higher oil consumptions, since the Italian transportation sector is mainly road-oriented, with less than 15 % of all goods transported by rail. Accordingly, the values indicate that the main environmental impacts (82 %) derive from fossil fuel used to produce liquefied fuels used in the transport sector (e.g., diesel oil). In addition to the direct consumption of primary energy carriers for the biomass input treatments, the transportation process for delivering wood logs and pellet bags contribute significantly to the climate change and fossil depletion categories. In particular, repercussions are more significant when feedstock is imported from other regions or foreign countries. Overall, the transportation of wood logs covers longer distances than that of pellet bags, and the impact on the pellet stove scenario is, on average, less than 10 % as resulting from the sensitivity analysis ahead described.

The use of wood collected directly from the pruning of urban trees could entail potential benefits for the Italian municipalities since, generally speaking, tree prunes, when composting plants are not available, are disposed of in landfills, the worst waste treatment option of the European waste hierarchy (EU Directive 2008/98). Thus a way for a potential and positive exploitation of these residues might be inspired by a short chain, where cut wood is distributed/marketed to the local community as a fuel for domestic heating (in the form of logs or pellets). In the Lombardy Region, wood consumption for heating purpose amounted to about 1.5 Mt in 2008 (Pastorello and Dilara 2010), while separate collection of MSW embodied 900 kt organic waste, including compostable fraction and wood residues, in the same year (ISPRA 2012): assuming the wood share be one third of the total, according to some national estimations (ONR 2009), the short chain for feedstock supply might be up to 20 %.

Municipalities should organize cutting, storage, and distribution operations by reducing the negative features related to high moisture levels, usually due to short storage periods; indeed, moisture increases wood weight and the amount of pollutants emitted during the combustion phase (Nord-Larsen et al. 2011). Also, the distribution distance would not be long and the pruning period, specific for each tree species, would guarantee continuous storage and distribution.

As a recommendation, the study looked at the heating appliances for domestic environments modeled in accordance with the best available techniques. This means that the results describe some of the best contemporary performances, but these may vary from the average technological level because the cheapest biomass-based stoves with the worst combustion and removal efficiencies may be more widespread throughout the country (Pastorello and Dilara 2010).

3.2 Uncertainty and sensitivity analysis

As reported in Section 2.3, major uncertainty sources for the biomass scenarios were checked to verify how they may affect the cumulative results. As aforementioned, the wood

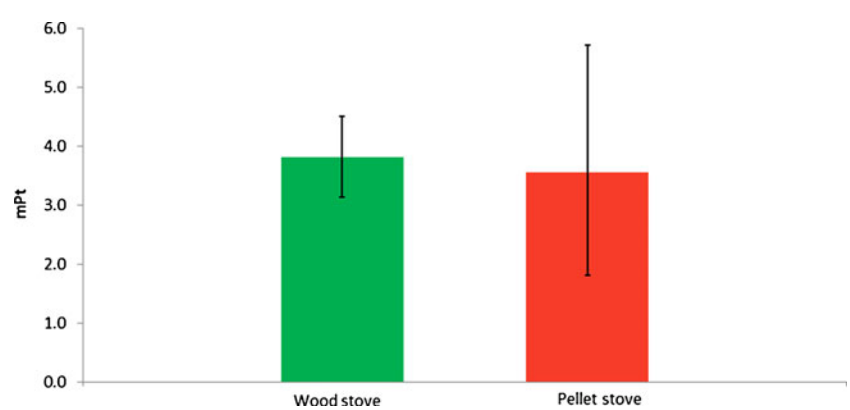

Fig. 2 Main uncertainty sources: bar chart show the ReCiPe single scores impact for the two scenarios

Table 5 Uncertainty scores for the main processes in terms of the squared standard deviation at 95 % confidence interval (SD^2)

Process	SD^2
Fuel amount and properties	1.5
Fuel transportation	2.0
Infrastructure (stove)	3.1
Emissions	1.9
Ash disposal	1.9

stove scenario is affected primarily by the transportation process such a consequence of the importing of wood logs over long distances; on the other hand, the pellet stove scenario is more sensitive to the energy requirements during the pelletizing process.

The overall results for the two scenarios, derived from the cumulative sum of each impact category and reported as ReCiPe single score in Fig. 2, are quite similar.

Uncertainty ranges, reported in the same figure, indicate a wider sensitivity for the pellet stove depending on the primary energy consumption from the pelletizing. A shift toward enhancing local biomass cultivation for the wood stove scenario, on one hand, and cleaner sources of energy for the pellet stove scenario, on the other hand, would lead to a decrease in the total environmental impact.

The energy demand in pelletizing was investigated in literature (Hellrigl 2004), but the data obtained were not very homogeneous. In particular, as shown from the bars, when the highest energy consumption estimate is considered, the pellet scenario results in a higher (nearly double) total impact than the wood stove, and it becomes environmentally disadvantageous. On the other hand, if the lowest value of energy consumption is considered, the global impact decreases to half of the total.

The transportation phase, in the wood stove scenario, is less significant, affecting the cumulative environmental impact by less than 10 %, despite the fact that around 25 % of the pellets sold in Italy are imported from European countries, mainly Austria and Slovenia (Cocchi et al. 2009; Junginger et al 2010). Unlike the previous case, the wood stove presents a lower variability due to fewer sources of uncertainty. The present situation in Lombardy Region is probably represented by the lower value, indicated from the minimum of the bar. In fact, as previously discussed, the abundance of Italian forest biomass (FAO 2011) allows most consumers to collect timber locally (Pastorello and Dilara 2010); however, if the total consumption of Lombardy increases, due to the spreading of such installations, importation may be necessary and it could bring about an increase in the total impact, as shown by the maximum value of the uncertainty bar.

Also, to test the robustness of the model, we carried out a sensitivity analysis performing a Monte Carlo analysis to check the reliability of the results for each midpoint category at a 95 % confidence level. Monte Carlo analysis was used for a statistical evaluation of the results for each midpoint from both scenarios. Standard deviation (SD) values were estimated for input and output data of each process using the data quality pedigree matrix by Weidema and Wesnaes (1996). The lognormal statistical distribution and iterative calculation number of 1,000 simulations were applied; the main calculated values for the SD^2 are listed in Table 5.

Figure 3 shows the Monte Carlo analysis results: on the *y*-axis, the five impact categories considered in the study are shown, while the *x*-axis shows the percentage rates achieved by scenarios at the end of iterative simulations. Blue bars show the number of times the wood stove scenario proved preferable to the pellet stove, and the brown bars represent the opposite situation. The scores obtained clearly indicate net contributions by the scenarios to each midpoint, validating the choice of inspecting the different categories separately instead of focusing on the single scores. Indeed, although the total score earned by the two scenarios is quite similar,

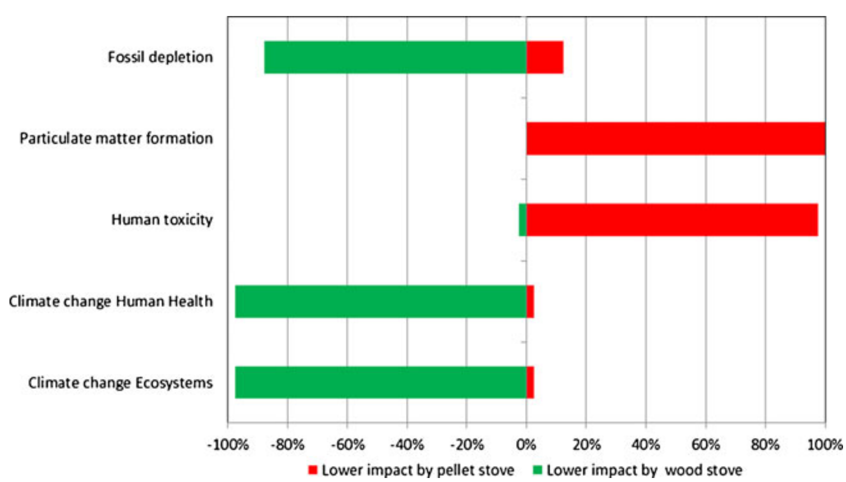

Fig. 3 Monte Carlo analysis results in terms of midpoint impact categories

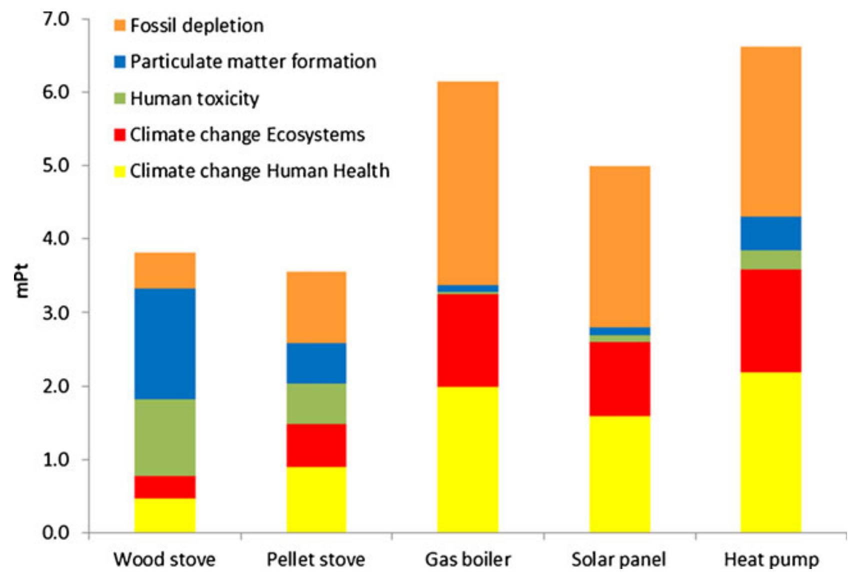

Fig. 4 Comparison of biomass-based scenarios and innovative domestic heating systems. Values are expressed in ReCiPe single scores (mPt)

each stove has a specific pattern that should be considered when comparing heating appliances for urban areas.

3.3 Comparison with alternative scenarios

A comparison of the most widespread alternative technologies for domestic heating was performed to assess qualitatively the contribution to the environmental midpoint categories involved in the study. The results of the comparison, obtained using the ReCiPe v.1.07 method, are reported in Fig. 4. Biomass stoves show the highest contribution to PMF and HT categories: as discussed previously, these effects result from the characteristics of biomass feedstock and justify the current concerns over the effect of biomass fuel appliances on urban air quality. In the same two categories, among the alternatives, the third highest contribution comes from the heat pump scenario, due to the high quantity of fossil fuel used to produce the electricity necessary for the appliance's operation; gas boiler and solar panel scenarios have negligible effects. In this sense, an improvement in heat pump effectiveness could derive from combination with a photovoltaic system that would lead to a reduction in particulate emissions as well as to positive returns in air conditioning during the summer season.

The remaining midpoints indicate the highest impacts for the alternative scenarios, mainly for fossil depletion and damage to human health and ecosystem from climate change. This is due to the energy-intensive production processes for high-tech materials included in those technologies. Also, while for gas boiler and solar panel scenarios sensible improvements would result from technological progress and efficiency increases, the heat pump scenario is even affected by the power production mix adopted by a country: thus if Italy would move toward renewable sources of electricity, significant benefits might result for such a scenario.

Lastly, the analysis performed limited the scope to thermal heat generation only, excluding the complementary functions of systems such as power generation. A comprehensive knowledge of the issue should, however, include the energy and economic returns obtained from the systems investigated.

4 Conclusions

Following the recent initiatives promoted by some Italian regions to decrease the particulate matter emitted by biomass-based domestic heating systems, a LCA approach was used in the study to compare two different appliances: a wood stove and a pellet stove, both modeled according to the BATs definition.

In general, it appears that a life cycle approach can support the choice of a better domestic heating system and would promote policy initiatives on a more consistent basis. Specifically, LCA allows a thorough investigation of different environmental impact categories, which can overcome partial analyses or uncompleted evaluations: in this sense, the comparison between the scenarios of domestic heating by wood and pellet stoves can lead to different conclusions in terms of environmental benefits whether the climate change and fossil depletion impact categories are considered besides the PMF and HT. Moreover, the methodology gives the advantage to quantify every single process contribution, helping to understand which are the more critical aspects to be tackled for reducing the total burdens to the environment.

Anyway, the study shows that a preference for latest-generation pellet stoves, with efficient emission control systems, and a ban on obsolete wood stoves might lead to significant improvements in the quality of air in urban areas as combustion emissions are among the most impacting causes, even though further environmental benefits would

come from a reduction in the energy consumption of the pelletizing process. However, a shift toward renewable sources in power production would encourage alternative heating systems: a solar panel, combined with a gas boiler for meeting winter heating needs, seems to greatly reduce particulate matter formation and negative human toxicity effects. Complementary initiatives at the municipal level, such as the commercialization of wood-based fuels (e.g., pellet bags) from tree pruning operations for the purpose of implementing a short biomass feedstock chain and raising the awareness of social communities, or even financial incentives to promote green heating technologies, are some measures which can be taken by local governments to make a shift toward innovative residential heating systems based consistently on renewables (Madlener and Koller 2007; Verma et al. 2009).

Lastly, although a more complete presentation of the environmental impacts may be extended to complementary midpoint and endpoint categories, most of them assess burdens on a wide-scale level as national or geographical macro-areas. Instead, a specific impact assessment for metropolises and municipalities would require customized characterization models because many physical and chemical parameters may vary greatly depending on local conditions. Thus, the creation of local databases and midpoint impact categories, validated with environmental monitoring system results, would help to provide LCA models based on local parameters, for an impact assessment at a more micro-area level.

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